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Physics

Statistical Thermodynamics of the Fermi Gas at Presence of the Relativistically Intense EM Field

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ABSTRACT. We discuss some aspects of interactions of high-frequency electromagnetic (EM) waves with quantum Fermi gas, assuming that the intensity of EM waves is sufficiently large. Relativistic statistical thermodynamics of quantum electron-ion gas at presence electromagnetic waves is considered. In this case the distribution function of particles becomes anisotropic, due to high power EM waves. By the new distribution function we study all the thermodynamic quantities as function of densities, temperatures and the amplitude of EM waves. We investigate the cavitation phenomenon of degenerate Fermi electron gas. We obtain a novel set of adiabatic equations. For two cases we obtain expressions of the specific heat, which is strongly dependent from the amplitude of EM waves, namely, the coefficient of the electron specific heat increases with the increase of the amplitude of EM waves. *© 2016 Bull. Georg. Natl. Acad. Sci.*

Key words: degenerate Fermi gas, relativistically EM waves, quantum electron cavitations.

In recent years one of the most important problems in plasma physics is the study of nonlinear interactions of intense electromagnetic (EM) waves with plasmas [1-16]. More recently, a great deal of attention was devoted to the study of the properties of electron-ion and electron-positron-ion quantum Fermi plasmas [17-31]. Such interest is motivated by its potential application in modern technology, e.g. metallic and semiconductor nanostructures - such as metallic nanoparticles, quantum wall and quantum dots, nanoplasmonic devices, quantum X-ray free-electron lasers, etc.

Moreover, quantum electron-ion or electron-positron-ion plasmas are common in planetary interiors, in compact astrophysical objects (e.g. the interior of whitedwarf stars, magneto spheres of neutron stars and etc.), as well as in the next generation intense laser-solid density plasma experiments.

Despite extensive theoretical efforts (for review see [17] references therein) since then there were questions and issues to be clarified. Answers to some salient questions are given in references [20,31], with a new type of quantum kinetic equations of the Fermi particles of various species and a general set of fluid equations. This kinetic equation for the Fermi gas was used to study the propagation of small longitudinal perturbations, deriving a quantum dispersion equation. Later the dispersion properties of linear oscillations of quantum electron-ion [22-23], and electron-positron-ion [25] plasmas, as well as at neutral He^3 [32], where studied. The effects of the quantization of the orbital motion of electrons and the spin of electrons on the propagations of longitudinal waves in the Fermi gas are also reported recently [26].

Quite recently an adiabatic magnetization process was proposed in Ref. [27] for cooling the Fermi electron gas to ultra-low temperatures. New aspects of the plasma of a photon gas in the nonlinear classical electron-ion plasmas were considered in Ref. [33].

First Law of relativistic thermodynamics, Boltzmann H-theorem for photon gas and adiabatic photon self-capture was investigated in Ref. [16].

Nonlinear propagation of intense EM waves in a hot electron-positron or electron-positron-ion plasmas was investigated in [11,12,14,34-36] and has shown that distribution function of particles becomes anisotropic [37-38].

The study of relativistic thermodynamics of a Fermi gas, of sufficiently low temperature and in a relativistically intense EM wave is of fundamental significance.

In this letter, we shall investigate degenerate Fermi gas in the presence of a strong EM field and calculate the thermodynamically quantities developing the statistical mechanics in the relativistically intense EM waves.

Quantum Anisotropic Distribution Function

Let us now consider a system which is a diluted gas composed of electrons, ions and photons (e+i+γ or electrons, positrons, ions and photons ($e^-+e^++i+\gamma$), and describe this compressible and continuous medium in terms of its macroscopic properties such entropy, pressure, density, etc. It was shown in Ref.[16,37-38] that in the case of the relativistically intense (circularly polarized) EM waves propagation into a plasma, the photon momentum $\frac{e_\alpha \vec{A}_\perp}{c}$ ($\vec{A}_\perp$ is the perpendicular component of the vector potential of the EM waves, α stands for the partial species) can be much larger than the perpendicular component of the thermal momentum of particles. Hence, the perpendicular component $\vec{p}_{\perp\alpha}$ of particles is just $\vec{p}_{\perp\alpha} = -\frac{e_\alpha \vec{A}_\perp}{c}$, whereas the momentum $p_{\|\alpha}$ of particles along the propagation of EM waves remains thermal.

Subsequently we will consider only electron degenerate Fermi gas.

In the quantum degenerate Fermi gas, we shall consider the case, when the photon momentum $\frac{e\vec{A}_\perp}{c}$ is much larger than the perpendicular components of the Fermi momentum of electrons $p_F^\perp = \left(3\pi^2\right)^{1/3} \hbar \cdot n^{1/3}$, whereas the momentum of electrons along the propagation of EM waves remains Fermi momentum $p_F^\|$. Both momenta $\vec{p}_\perp = \frac{e\vec{A}_\perp}{c}$ and $p_\| = p_z$, can be arbitrary (relativistic or non-relativistic, also we suppose that EM waves are propagating along the *z* direction in a Cartesian coordinate system). In that case of Fermi sphere $p_{Fx} \sim p_{Fy} \sim p_{Fz} \sim p_F$, at percent strong EM waves shape of Fermi changes $\left(p_{\perp F}^2 >> p_{\|F}^2\right)$ and become coaxial cylinder. In this case the relativistic kinetic energy reads

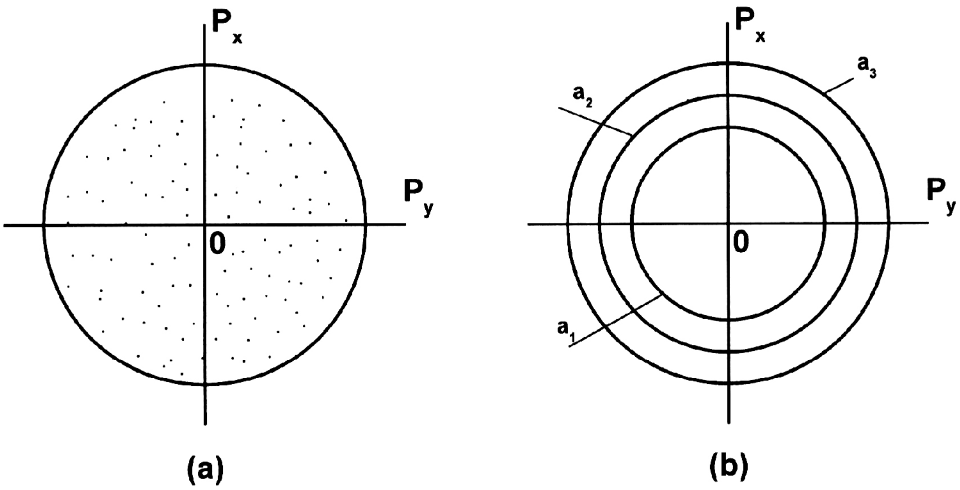

Fig. 1. (a) shows free electrons without EM field (a=0), (b) free electrons in EM field (a≠0).

$$\varepsilon_k = c\sqrt{m_0^2c^2+p_\perp^2+p_\parallel^2} - m_0c^2 \approx m_0c^2\left(\sqrt{1+a^2}-1\right)+\frac{p_\parallel^2}{2m_*},$$

where $a^2 = \left(\frac{e\vec{A}_\perp}{m_0c^2}\right)^2$ and $m_* = m_0\sqrt{1+a^2}$. In the general, in this case can be $m_0c^2\sqrt{1+a^2} > \frac{p_\parallel^2}{2m_*} > m_0c^2$.

Non-relativistic case we have $\varepsilon_k = \frac{p_\perp^2}{2m_0}+\frac{p_\parallel^2}{2m_0} = \frac{\left(e\vec{A}_\perp\right)}{2m_0c^2}+\frac{p_\parallel^2}{2m_0}$.

If EM field is absent $a = 0$ a uniform filling of the Fermi sphere by the points depicting the allowed states corresponds to continuous energy spectrum $E\left(p_x + p_y + p_z\right)$, where p_x, p_y, p_z run through continuous sets of values from 0 to p_F (See Fig.1a). Application of the intense EM waves does not change the total number of electrons, but causes their redistribution and the allowed state in the plane $p_z = const$ is one given orbit (define by a^2, as shown in Fig. 1(b)).

When a three dimensional analogue is considered, this means that in the strong EM field allow state is condensed on the surface of coaxial cylinder parallel to p_z axis (See Fig.2).

For a Fermi distribution function with a chemical potential $\mu > m_0c^2\sqrt{1+a^2}$ we have at $T = 0$ the situation shown in Fig. 3. The chemical potential at $T = 0$ is just equal to the energy of the highest occupied state, i.e. $\mu = m_0c^2\sqrt{1+a^2+\frac{p_F^2}{m_0^2c^2}}$.

Thermodynamics of Fermi gas

We now introduce the basic definitions in the rest system of given plasma component, namely, the density,

$$n\left(\vec{r},t\right) = 2\cdot\int d\vec{p}\cdot f, \tag{1}$$

where the factor 2 is on account of the particle spin,

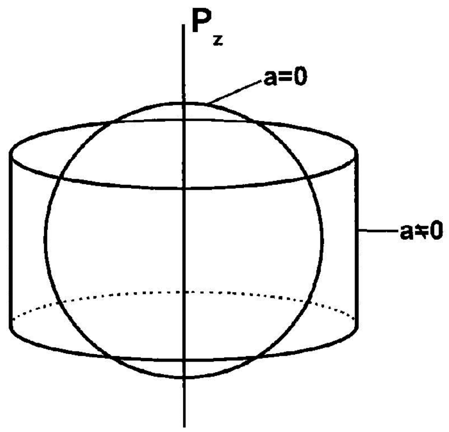

Fig. 2. When a three dimensional analogue is considered, this means that in the strong EM field allow state is condensed on the surface of coaxial cylinder parallel to p_z axis.

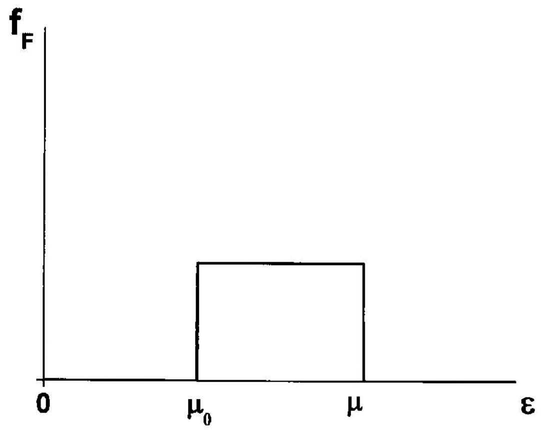

Fig. 3. Fermi distribution function with a chemical potential $\mu > \mu_0 = mc^2\sqrt{1+a^2}$ at T=0.

$$f = \frac{B}{\exp\left(\beta\left(\sqrt{1+a^2+u^2}-\bar{\mu}\right)\right)+1}, \tag{2}$$

B-is the normalization constant which is defined as

$$B = n_0\int_{-\infty}^{\infty} dp_{\|}\left[\exp\left(\frac{c\sqrt{m^2c^2+p_{\|}^2}-\mu}{T}\right)+1\right]^{-1}, \tag{3}$$

n_0 - is the density of electrons at the absent EM field, T is the temperature and in all subsequent formulae will be measured in energy units. Introduced the following notation: $u = \frac{p_{\|}}{mc}$, $\bar{\mu} = \frac{\mu}{mc^2}$, $\underline{\mu} = \frac{\bar{\mu}}{\sqrt{1+a^2}}$, $\beta = \frac{mc^2}{T}$,

also $z = \frac{u}{\sqrt{1+a^2}}$, $\underline{Q} = \frac{T}{mc^2\sqrt{1+a^2}}$.

Assuming the Fermi degeneracy temperature $T_F = \frac{\varepsilon_k}{k_B}$ (k_B is the Boltzmann constant) much higher than Fermi gas temperature, the Fermi distribution function is in a good approximation described by the Heaviside step function $H(\mu-\varepsilon)$ from which follows $\mu = m_0c^2\sqrt{1+a^2+u_F^2}$.

If absent EM waves, i.e. $a^2 = 0$, the density of electrons is defined as

$$n_0 = 2m_0c\cdot B\int_0^{\infty} du\cdot f = m_0cB\int_0^{\infty} du\cdot H\left(\bar{\mu}-\sqrt{1+u^2}\right) \text{ or } B = \frac{n_0}{2m_0c\sqrt{\bar{\mu}^2-1}} \tag{4}$$

At $T = 0$, the distribution function of electrons f now reads as

$$f = \frac{n_0}{2m_0c\sqrt{\bar{\mu}^2-1}}\cdot H\left(\bar{\mu}-\sqrt{1+a^2+u^2}\right). \tag{5}$$

For the density we obtain

$$n=\frac{n_0}{\sqrt{\bar{\mu}^2-1}}\cdot\sqrt{\bar{\mu}^2-1-a^2}. \tag{6}$$

The dynamics of relativistically circularly-polarized EM waves propagation in a relativistically hot electron-positron plasma has been considered and it is shown, that at a certain amplitude of the EM field, a cavitation phenomenon takes place [39]. This phenomenon takes place also in the degenerate Fermi electron gas, which follows from Eq. (6), that the density of electrons becomes zero at $a^2 \cong \bar{\mu}^2-1$.

Expression (6) shows that all electrons are ejected across the EM beam direction. This phenomenon can be called "quantum electron cavitation".

Two types of relativism were investigated in detail in classical plasmas [4,9, 34,37-38]. One is electrons in a strong EM field, in which may obtain relativistic velocities. The second one is when the thermal energy of the plasma electrons is of the order or larger than the energy at rest, it is the other type of relativism. In this case the thermal velocities of the electrons become of the order of the light speed.

In the case of the Fermi gas (EM field absent) is compressed, the mean energy of the particles increases. When it became comparable with m_0c^2, relativistic effects begin to be important. In this case the relativistic gas will be formed. The density of electrons should be $n=\frac{p_F^3}{3\pi^2\hbar^3}=6\cdot10^{29}\left(\frac{p_F}{m_0c}\right)^3\geq 6\cdot10^{29}cm^{-3}$ or more.

We now consider the case, when the thermal energy k_BT is much less than the Fermi energy ε_F. In this case the distribution function is appreciably different from unity in a narrow range of values of the energy $\varepsilon=m_0c^2\sqrt{1+a^2+u^2}$ close to limiting Fermi energy μ. The width of this transition zone of the Fermi distribution is of the order of k_BT. Thus, in this case the density of electrons for the non-relativistic limit

$$n=n_0\left(1-\eta^2\right)^{1/2}\left\{1-\frac{\pi^2}{24}\left(\frac{T}{\varepsilon_F}\right)^2\frac{1}{\left(1-\eta^2\right)^2}\right\}, \tag{7}$$

where $\eta=\frac{eA_\perp}{cp_F}$. For the relativistic limit

$$n=\frac{n_0}{\sqrt{\bar{\mu}^2-1}}\cdot\sqrt{\bar{\mu}^2-1-a^2}\left\{1-\frac{\pi^2}{6}\frac{\Theta^2\left(1+a^2\right)}{\left(\bar{\mu}^2-1-a^2\right)^2}\right\}. \tag{8}$$

The mean kinetic energy defined in the form

$$\langle\varepsilon_k\rangle=\frac{B}{n}m_0^2c^3\int_{-\infty}^{\infty}du\sqrt{1+a^2+u^2}\left\{H(\bar{\mu}-\bar{\varepsilon})+\left(\frac{1}{\exp\left(\frac{\bar{\varepsilon}-\bar{\mu}}{\Theta}\right)+1}-H(\bar{\mu}-\bar{\varepsilon})\right)\right\}-m_0c^2. \tag{9}$$

Again we consider the case, when the thermal energy k_BT is much less than the chemical potential. Thus, the mean kinetic energy can be rewritten as

$$\langle \varepsilon_k \rangle = \frac{m_0 c^2}{2} \left\{ \bar{\mu} + \frac{(1+a^2)}{\sqrt{\bar{\mu}^2 - 1 - a^2}} \ln \frac{\bar{\mu} + \sqrt{\bar{\mu}^2 - 1 - a^2}}{(1+a^2)^{1/2}} + \frac{\pi^2}{3} \Theta^2 \left[\frac{\bar{\mu}\left(\bar{\mu}^2 - 2(1+a^2)\right)}{(\bar{\mu}^2 - 1 - a^2)^2} + \right.\right.$$

$$\left.\left. \frac{1}{2} \frac{(1+a^2)}{(\bar{\mu}^2 - 1 - a^2)^2} \left\{ \bar{\mu} + \frac{(1+a^2)}{\sqrt{\bar{\mu}^2 - 1 - a^2}} \ln \frac{\bar{\mu} + \sqrt{\bar{\mu}^2 - 1 - a^2}}{(1+a^2)^{1/2}} \right\} \right] \right\} - m_0 c^2. \quad (10)$$

Non-relativistic limit for the mean kinetic energy we have

$$\langle \varepsilon_k \rangle = \frac{(eA_\perp)^2}{2 m_0 c^2} + \frac{\varepsilon_F}{3}(1-\eta^2) \left\{ 1 + \frac{\pi^2}{6} \left(\frac{k_B T}{\varepsilon_F} \right)^2 \frac{1}{(1-\eta^2)^2} \right\}. \quad (11)$$

We now define the specific heat for the Fermi electron gas for two cases. Relativistic limit (10)

$$C_V = \left(\frac{\partial \langle \varepsilon_K \rangle}{\partial T} \right) = \frac{\pi^2}{3} \frac{T k_B^2}{m_0 c^2} \times$$

$$\left\{ \bar{\mu}\left(\bar{\mu}^2 - 2(1+a^2)\right) + \frac{1}{2}(1+a^2) \left[\bar{\mu} + \frac{(1+a^2)}{\sqrt{\bar{\mu}^2 - 1 - a^2}} \ln \frac{\bar{\mu} + \sqrt{\bar{\mu}^2 - 1 - a^2}}{(1+a^2)^{1/2}} \right] \frac{1}{(\bar{\mu}^2 - 1 - a^2)^2} \right\}. \quad (12)$$

Non-relativistic case (11) the specific heat and entropy reads as

$$C_V = \left(\frac{\partial \langle \varepsilon_K \rangle}{\partial T} \right) = \frac{2}{3 \cdot 3} \left(\frac{\pi}{3} \right)^{2/3} \frac{k_B^2}{\hbar^2} \frac{T}{n^{2/3}} \frac{m}{(1-\eta^2)} \quad (13)$$

$$S = \frac{2}{3 \cdot 3} \left(\frac{\pi}{3} \right)^{2/3} \frac{k_B^2}{\hbar^2} \frac{T}{n^{2/3}} \frac{m}{(1-\eta^2)}, \quad (14)$$

whereas for the entropy we have the same expression as equation (13), as it was expected.

We know that in all temperature regions a metal consists of two subsystems: a crystalline Lattice of ions and a free electron gas. Therefore, the specific heat of a metal can be presented as a sum of two items:

$$C_V = C_V^{lat} + C_V^e, \quad (15)$$

where C_V^{lat} is the specific heat of the lattice and for $\Theta << T$

$$C_V^{lat} = 3 k_B N, \quad (16)$$

for $\Theta >> T$

$$C_V^{lat} = \frac{12\pi^4}{5} k_B N \left(\frac{T}{\Theta} \right)^3, \quad (17)$$

where $\Theta = \frac{\hbar\omega}{k_B}$ is the Debye characteristic temperature, N is the total number of particles. C_V^e is the free electron isotropic gas. For $T >> T_F$

$$C_V^e = \frac{3}{2} k_B N \quad (18)$$

and for $T << T_F$

$$C_V^e = \frac{\pi^2}{2} k_B N \left(\frac{T}{T_F} \right), \tag{19}$$

where
$$T_F = \frac{\left(3\pi^2\right)^{2/3} \hbar^2 n^{2/3}}{k_B \, 2m_e}, \tag{20}$$

$n = \frac{N}{V}$ is the density of electrons.

Comparison between C_V^{lat} and C_V^e show us that for the temperature $T \geq 1$ degree C_V^{lat} is always more than C_V^e. We show that the specific heat of electrons at $T = 1$ degree or more can be greater than $C_V^{lat} \sim T^3$ for the case of $\eta^2 \to 1$ (see Eq. (13)).

Since the entropy remains constant in an adiabatic process, from equation (14) follows

$$\frac{T}{n^{2/3}} \frac{1}{\left(1-\eta^2\right)} = const = \frac{T_0}{n_o^{2/3}}. \tag{21}$$

This is new adiabatic equation.

In the absence of EM fields $a^2 = 0$ the above expression (21) reduces to well-known expression, given in reference [40].

Note that equation (21) is an adiabatic equation and it should be emphasized that this adiabatic equation is the function of three variables – the density, the temperature and the amplitude EM waves.

If we suppose that the density of the Fermi gas is constant, then the adiabatic equation reduces to

$$T = T_0 \left(1-\eta^2\right), \tag{22}$$

which show that at $\eta \to 1, T \to 0$. Thus, we have demonstrated the adiabatic cooling the Fermi electron gas to ultra-low temperatures.

We now derive the perpendicular component of the pressure using the distribution function (5) for electrons

$$P_\perp = \frac{1}{3} c^2 \int \left(p_x^2 + p_y^2\right) \frac{f}{\varepsilon} d\vec{P}.. \tag{23}$$

After integration of expression (23), we obtain

$$P_\perp = \frac{1}{3} \frac{mc^2 n}{\sqrt{\bar{\mu}^2 - 1 - a^2}} a^2 \left\{ \ln\left(\bar{\mu} + \sqrt{\bar{\mu}^2 - 1 - a^2}\right) - \ln\left(\sqrt{1+a^2}\right) \right\}. \tag{24}$$

Non-relativistic approximation the pressure $P_\perp$ reads as

$$P_\perp = \frac{1}{3} \frac{n}{m} \cdot p_F^2 \cdot \eta^2 \tag{25}$$

where n is the density of electrons defined by Eq. (7).

Next, for the parallel component of the pressure we obtain

$$P_\parallel = \frac{1}{3} c^2 \int p_\parallel^2 \frac{f}{\varepsilon} dp_\parallel. \tag{26}$$

Use of expression (2) in Eq. (26) yields

$$P_{\parallel} = \frac{1}{3}\frac{nmc^2}{\sqrt{\bar{\mu}^2 - 1 - a^2}} \cdot \frac{1}{2}\left\{\bar{\mu}\sqrt{\bar{\mu}^2 - 1 - a^2} - \left(1 + a^2\right)\ln\left(\frac{\bar{\mu} + \sqrt{\bar{\mu}^2 - 1 - a^2}}{\sqrt{1 + a^2}}\right)\right\}. \quad (27)$$

Non-relativistic limit $\varepsilon << 1$ and $a^2 << 1$ we obtain

$$P_{\parallel} = \frac{1}{9}\frac{n}{m}P_F^2\left(1 - \eta^2\right). \quad (28)$$

Note that Expression (24), (27) and (28) become zero when a cavitation phenomenon takes place.

Summary

We have created the relativistic thermodynamics of quantum Fermi electron gas. We have studied the thermodynamic properties of a Fermi gas in the presence of a relativistically, as well as non-relativistically intense EM waves and investigated all the thermodynamic quantities as a function of density, temperature and radiation. We have shown, that at certain amplitude of the EM field, a cavitation phenomenon takes place in the degenerate Fermi gas.

The relativistic and non-relativistic expression of the specific heat is explicitly found. We have shown that EM field sufficiently changes the equation of state. We have obtained a novel set of adiabatic equations. A novel adiabatic equation implies that at the constant density the increase of the amplitude of EM field consequently leads to the temperature decrease as $T \approx \left(1 - \eta^2\right)$ for non-relativistic case. The results of the present paper may be substantial interest in connection with the applications in modern technology and also in astrophysical plasmas, e.g. pulsars, white dwarf stars, black holes etc.

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ფიზიკა

ფერმი გაზის სტატისტიკური თერმოდინამიკა რელატივისტურ მძლავრ ელექტრომაგნიტურ ველში

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შესწავლილია ფერმი გაზის რელატივისტური თერმოდინამიკა საკმარისად დაბალ ტემპერატურაზე და რელატივისტურ მძლავრ ელექტრომაგნიტურ ველში. გამოკვლეულია გადაგვარებული დაკვანტური ელექტრონ-იონური ფერმი გაზის თვისებები ძლიერი ელექტრომაგნიტური ველის არსებობისას. ამ დროს ნაწილაკთა განაწილების ფუნქცია ხდება ანიზოტროპული და ყველა თერმოდინამიკური სიდიდე წარმოიდგინება, როგორც სიმკვრივის, ტემპერატურის და ელექტრომაგნიტური ტალღების ამპლიტუდის ფუნქცია. გამოკვლეულია გადაგვარებული ელექტრონული ფერმი გაზის კავიტაციის მოვლენა. მიღებულია ახალი ადიაბატური განტოლებები. დადგენილია, რომ სითბოტევადობის კოეფიციენტი იზრდება ელექტრომაგნიტური ტალღების ამპლიტუდის ზრდასთან ერთად.

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